Biomechanical studies of spinal manipulative therapy (SMT): quantifying the movements of vertebral bodies during SMT

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The relative movements between vertebral bodies T10 and T11, and T11 and T12 were measured during clinical-type SMTs to T11 in unembalmed post-rigor human cadavers, using embedded stainless steel bone pins and high speed cinematography. Significant relative movements between target and adjacent vertebrae occurred primarily in sagittal and axial rotation during the thrust phases of the SMTs. The relative positions of the vertebral bodies were compared at similar force levels, before and after the rapid thrust phases. The sagittal angles between T11 and T12 following the SMTs, were significantly different from their pre-thrust values. Two non-invasive methods (surface markers and uni-axial accelerometers) were compared to the invasive bone pins, in order to assess their suitability to accurately measure posterior-anterior translation. The results showed that both non-invasive techniques significantly underestimated the *absolute* movements of all vertebral bodies during the SMTs. The *relative* posterior-anterior translations using the non-invasive techniques however, were not significantly different from those determined from the bone pins.
(JCCA 1994; 38(1):11–24)

La cinématographie ultra-rapide et les aiguilles effractives en acier inoxydable ont été utilisées sur des cadavres pour mesurer les mouvements relatifs entre les vertèbres D-10-D-11 et D-11-D12 lors de manipulations vertébrales sous D-11. La dépouille humaine était en phase post-rigidité et non-embaumée. L'examen a révélé durant l'ajustement des mouvements relatifs importants entre l'endroit visé et la vertèbre adjacente, principalement sur le plan saggital et une rotation axiale. La position relative des corps vertébraux soumis à des ajustements de force égale comprend : avant et après l'ajustement. Les angles saggitaux entre les vertèbres D-11 et D-12, suite aux TMV, se révélèrent passablement différents de ce qu'ils étaient avant le test. Deux méthodes non-invasives (marqueurs de surface et accéléromètres uniaxials) furent comparées aux aiguilles invasives de façon à évaluer leur aptitude à mesurer efficacement le transfert postérieur-antérieur. Les résultats ont indiqué que les deux techniques non-invasives ont largement sous-estimé les mouvements absolus de tous les corps vertébraux pendant les TMV. Les transferts relatifs postéro-antérieurs mesurés au moyen de techniques non-invasives ne démontraient pas de différences significatives par rapport aux transferts obtenus au moyen des aiguilles invasives.
(JCCA 1994; 38(1):11–24)

Introduction

Spinal manipulative therapy (SMT) is a mechanical intervention. Whether the mechanism by which spinal manipulation can achieve beneficial results for the patient is purely mechanical (e.g. a physical realignment of the vertebrae), a physiological response induced by the mechanical perturbation (e.g. induced immunological or reflex effects), or some combination thereof, is still unclear. At the University of Calgary, we are interested in the mechanics of spinal manipulation. That is to say, we are interested in the forces exerted by chiropractors onto the spines of patients, and the subsequent movements that occur between the vertebral bodies of patients. In 1991, we summarized the research that we had been conducting in the Human Performance Laboratory at the University of Calgary up to that point.[1] The emphasis of that work was twofold: investigating the effects of SMT on the mechanics of walking; and quantifying the forces exerted by clinicians onto patients during SMT to the cervical,

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thoracic and sacroiliac regions. Typically, walking symmetry improved in patients following treatments. By using pressure pads (EMED), we were able to measure the vertical force components during the preload and thrust phases of SMT. We found significant relationships between preload and peak thrust magnitudes, and suggested that clinicians could perhaps control peak thrust forces by being particularly sensitive to the forces exerted during the preload phase, where there is sufficient time to make the necessary adjustments.[2]

The research presented here is a logical extension of the long-term goal of our work; to understand the precise mechanics of SMT, and the mechanical and neurophysiological effects SMT has on patients. In this review, the following three concepts will be addressed.

1. Do relative movements occur between target and adjacent vertebrae during SMT?
2. Do vertebrae return to the same relative positions following an SMT?
3. Do non-invasive techniques for measuring the movements of vertebral bodies yield the same values as invasive techniques?

Rationale
In order to measure the absolute, and more importantly, the relative movements of vertebrae during a clinical treatment to a live patient, one is restricted to using a non-invasive procedure. Bone imaging techniques, such as x-ray, fluoroscopy, and magnetic resonance imaging (MRI) are useful approaches when studying static situations, or when movements take place slowly. During many types of therapeutic manipulations however, the forces are applied rapidly and the subsequent movements of the vertebral bodies are equally fast.

Studies involving the measurement of vertebral body movements during any type of SMT in living humans are very rare.[3] We decided to investigate the absolute and relative movements between target and adjacent vertebrae during a clinical-type of SMT to unembalmed post-rigor human cadavers. With cadavers, the selected vertebrae could be marked directly, and the movement of the markers could be quantified using high speed cinematography. Thus, the dynamic translations and rotations of the vertebrae could be assessed in three dimensions.

It was never our intention to use the data derived from our cadaveric studies to make specific predictions about the mechanical responses of the spine to SMT in living patients. Rather, we were interested in investigating what types of absolute and relative movements would be dominant for a specific type of manipulation, and whether or not relative movements between adjacent vertebrae could be measured. If a manipulation is delivered in exactly the same way to a cadaver, as to a live patient, our expectation would be that the same general pattern of the movement would be present in both cases, although the magnitudes of the applied forces and absolute movements may differ between the cadavers and the live patients. In the cadavers, we have only the passive structural components to offer

resistance to the applied manipulative forces. It is likely that the active components, such as muscle tonus, and thoracic and abdominal pressures, would exert a bracing or stabilizing effect on the vertebral column, over and above that afforded by the passive ligamentous and bony structures. However, the ways in which two vertebral bodies are able to move relative to one another depends ultimately upon the bony geometry, particularly of the articular facet joints.[4,5] Despite possible differences in tissue properties between the living and cadaveric states, bony geometry will remain the same. Therefore, the goal of this work was essentially to explore what types of relative movements occur between veterbrae during a genuinely-clinical type of SMT, to enhance to readers' awareness of the mechanical consequences of SMT, and to show that there is a necessity for a more complete understanding of the mechanical behavior of the spine during manipulative therapy, in order to ultimately explain the mechanisms by which SMT continues to successfully alleviate neck and back pain.

Measuring the absolute and relative linear and angular movements of vertebrae during a clinically-relevant SMT to cadaveric specimens represented the base from which we would proceed to devise a non-invasive method for measuring intervertebral movements in clinical situations. The movements detected with the bone-embedded markers would constitute our criterion measures. We decided to test two non-invasive techniques against our criterion values for their ability to detect a particular type of movement during the prescribed SMT. These were small surface markers, and uni-axial accelerometers, respectively, placed on the skin over the target (the vertebra receiving the spinal manipulative thrust) and the adjacent vertebrae. Both non-invasive methods were designed to record movements in the posterior-to-anterior (or anterior-to-posterior) direction only. The extent to which the surface measures reflected the values determined by the criterion markers would provide information about how to continue the design of a more complete non-invasive method, suitable for the clinical environment. Interestingly however, despite using a posterior-to-anterior thrust as our prescribed SMT, our criterion measurements suggested that *relative* rotations, particularly in the sagittal plane, were the dominant relative movements between vertebrae, while posterior-to-anterior translations were the most substantial movements, in an *absolute* sense. It is hoped that the reader will be able to develop an impression of how our work has progressed, and how we ultimately expect to contribute to the general understanding of spinal mechanics during SMT.

Methodology
Two unembalmed post-rigor male cadavers (aged 77 years each) were obtained from the Department of Anatomy at the University of Calgary, and used in succession. A cadaver was placed in the prone position on a stainless steel post-mortem table, with the arms extended and lying along the sides of the torso. The chiropractor located the thoracic vertebrae T10, T11 and T12, by palpation. Small incisions (approximately 5–7 mm) were
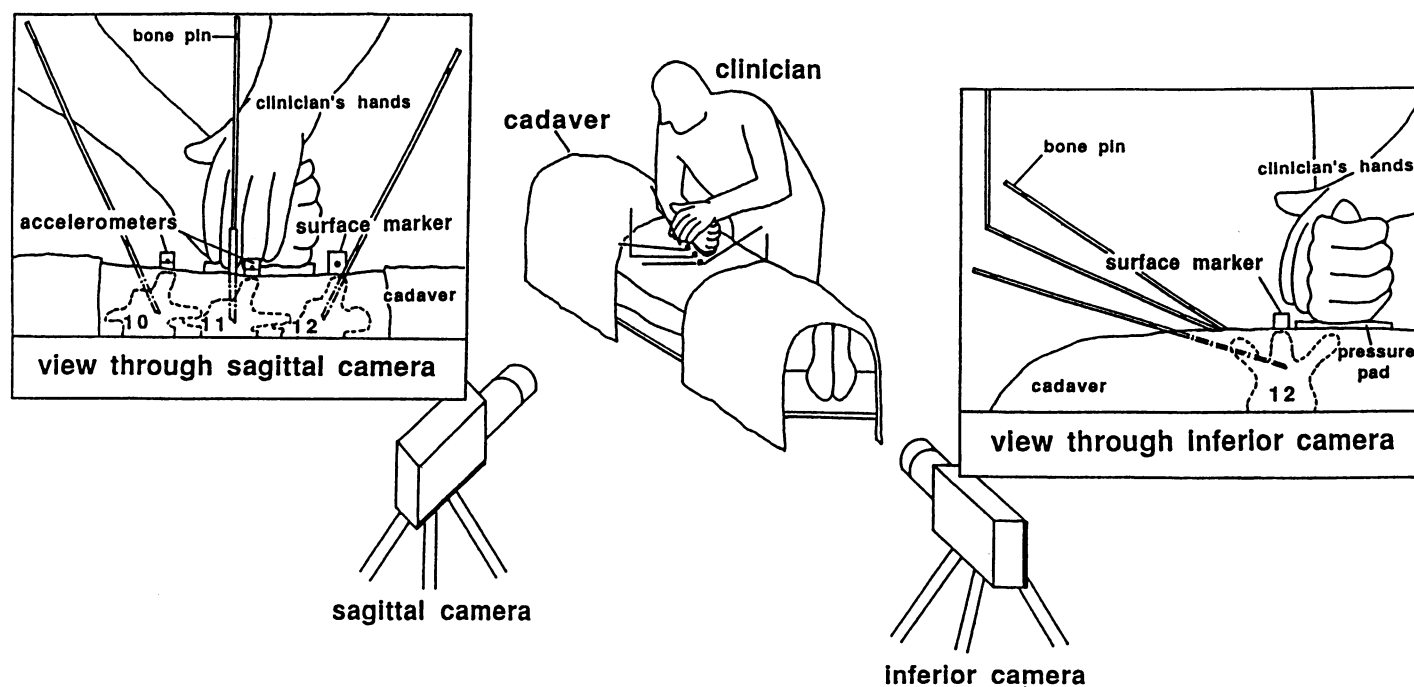
Figure 1 A schematic diagram of the experimental setup is shown. See text for further explanation.

made through the skin and the epaxial muscular and connective tissues, so that stainless steel bone pins (catheter lead wires, 229 mm × 2.5 mm, Zimmer, Indiana) could be threaded into the vertebral bodies of T10, T11 and T12. The locations of the pins were verified by radiography and dissection following the experiments. Two pins were inserted into T10 and T12 to project into the sagittal and transverse planes. A single pin was inserted into T11 to project into the transverse plane only. An aluminum pointer was subsequently attached to the end of the pin in T11, so that sagittal rotations could be measured without interferring with the clinician performing the adjustments. Two 1.5 g uniaxial accelerometers [Dytran, 3115A, USA, sensitivity 10 mV/g (where g is graviational acceleration) and frequency range 1 Hz to 20 kHz], were attached to the skin over the spinous processes of T10 and T11, or, T11 and T12 using double-sided tape. A small wooden bead was used as the surface marker for either T10 or T12, depending upon the location of the accelerometers. It too was attached using double-sided tape. Finally, a pressure pad (EMEDinc., Munich) was taped over the transverse process of T11, so that the vertical forces exerted by the chiropractor onto the cadaver could be measured. Two high speed cine cameras (Locam, Model 51-0002, Redlake Corp., USA) were positioned to record the movements of the clinicians

hands, the cadaver, the stainless steel bone pins, the accelerometers, and the surface markers, in each of the sagittal and transverse planes respectively. The edge of the lens of the sagittal camera was located 160 cm from the sagittally-oriented bone pins. The edge of the lens of the inferior camera was located 240 cm from the transversely-oriented bone pin in T11. The cameras, and the pressure pad were set to record at 100 frames per second, and 100 pressure samples per second respectively. The voltage outputs from the accelerometers were recorded on magnetic tape for further analysis.

Thus, on the appropriate command, the pressure system, the accelerometers, and the cameras were activated in succession, following which the chiropractor would administer a clinical-type posterior-to-anterior adjustment to the right transverse process of T11, using a reinforced hypothenar contact. A schematic diagram of the experimental setup is shown in Figure 1. All of the recording equipment were synchronized electronically so that the forces and movements could be compared using a single time scale, within each test. Approximately 10 minutes passed between successive adjustments, while the cameras were being checked and/or reloaded, and files were being transferred and saved. A total of 10 adjustments of the aforementioned description were performed on each cadaver.
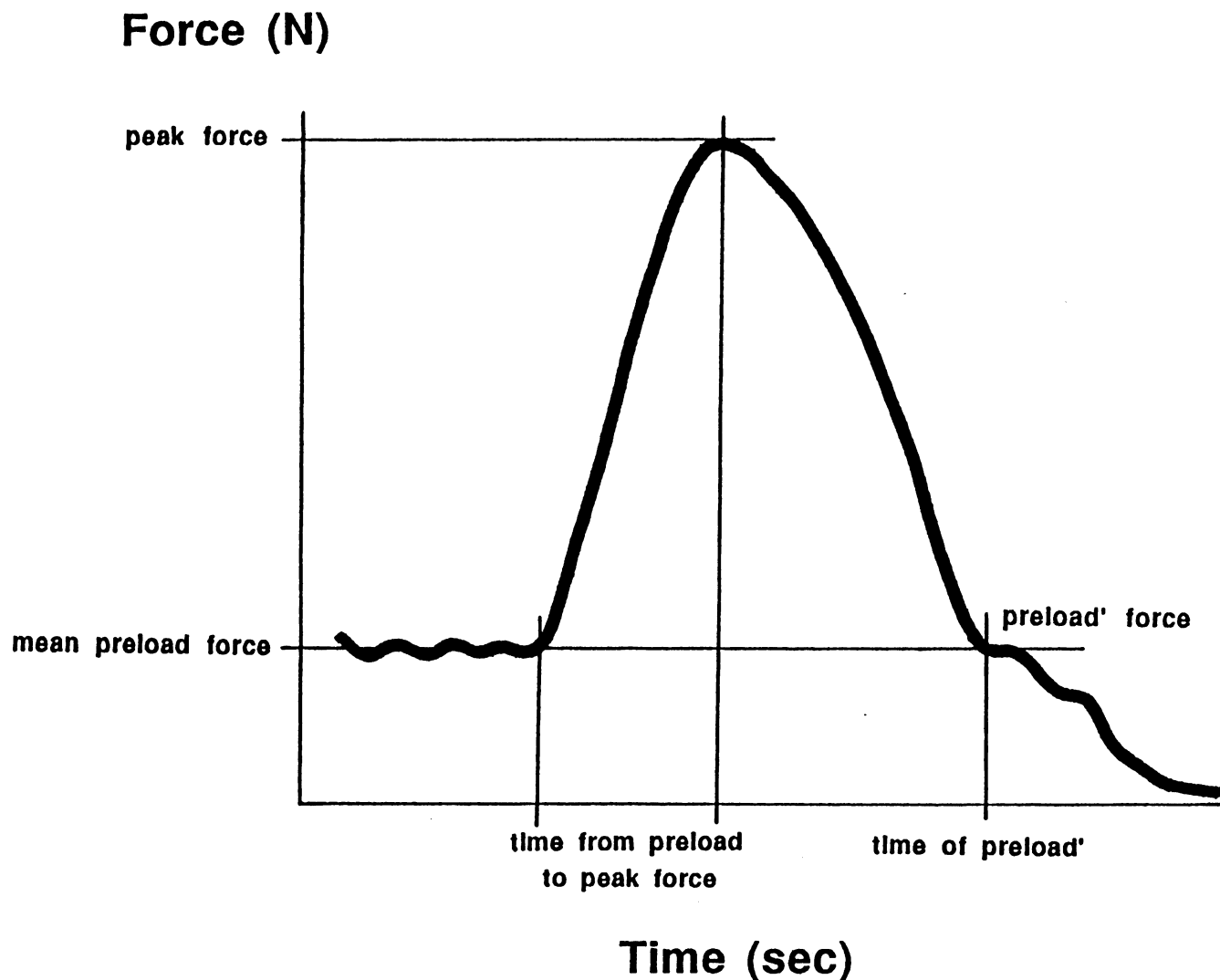
Force (N)

Figure 2 A typical vertical force-time curve for the prescribed SMT is shown. The specific force and time characteristics illustrated were obtained for each SMT from the output of the pressure pad. See text for further explanation.

Data analyses

Forces

A pressure pad was used to record the forces exerted perpendicularly to the thoracic spine. Pressures recorded using this pad were converted to forces, by dividing the pressures by the corresponding contact area during each 0.01 second interval throughout the duration of the SMT. A vertical force-time history of the prescribed SMT typically looked like that shown in Figure 2. A preload force was maintained for a variable, but brief time. This was followed by a rapid increase in force, to a maximum (peak) value. Subsequently, and usually less rapidly, the forces returned to the preload level, following which, the clinician would remove his hands, unloading the pad (see Herzog et al.[2] for a more comprehensive discussion of the forces

measured during SMT). For these analyses, a number of force-time variables were determined for each thrust (Figure 2), and defined below.

The *preload force* was estimated from the mean of 10 sequential force values, preceeding the rapid increase in force during the thrust. The *peak force* was taken as the singularly greatest force measured during the thrust. The mean preload force was extrapolated to the end of the thrust. Where this extrapolation intersected with the force-time curve, was called *preload'*. The *time from preload to peak force* was estimated by the difference between the time at which the peak force occurred, and the time at which the force deviated from the preload level. The time at which the vertical force component returned to the preload magnitude, following the rapid thrust, was located and termed *time of preload'*. Finally, the *rate at which the thrust was*
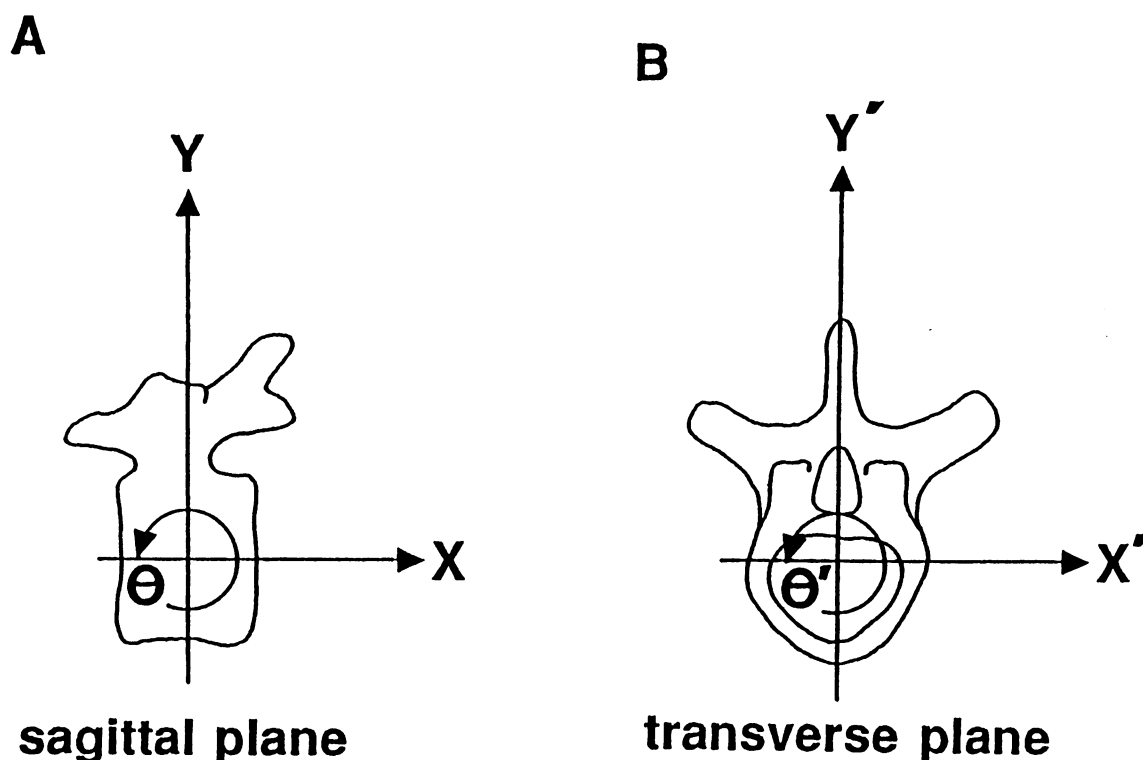
A

Y

sagittal plane

B

Y'

transverse plane

Figure 3 The orientations of the coordinate system used to quantify the translations and rotations in the sagittal and transverse planes are shown A and B respectively.) ⊖ represents angle. See text for further explanation.

applied, sometimes considered to be an important factor in determining a successful treatment,[6] was determined from the mean slope of the force-time curve during which the thrust force was increasing to the peak value (Figure 2).

Absolute and relative movement of bone pins and surface markers

The prescribed SMTs were fast thrusts. In order to measure the movements of vertebral bodies, which were equally fast, high speed cinematography was used. Sagitally- and transversely-oriented cameras recorded the movements of the embedded bone pins and surface markers (wooden beads and accelerometers). Portions of the bone pins which were exposed were covered with a layer of white hospital adhesive tape. One-centimetre intervals were marked on each bone pin along the exposed length so that each bone pin would function as its own scale. Two points on each of the bone pins, at least 10 cm apart, were digitized per frame in each of the sagittal and transverse SMT film sequences, in order to calculate the absolute linear and angular positions of each pin per frame. All linear positions were resolved with respect to the embedded tip of each bone within each vertebra. One point on each of the wooden beads and accelerometers were digitized per frame, in each of the sagittal and transverse sequences of each SMT. Incremental linear and angular positions were summed over the time frame of each SMT sequence, and translation-time curves and rotation-time curves were calculated. Figures 3A and B show the

orientation of the vertebrae with respect to the coordinate system used for the sagittal and transverse planes, respectively. The linear and angular movements that were calculated during the prescribed SMTs are shown below.

Bone pins: posterior-to-anterior translation
(Δy, $\Delta y'$, sagittal or transverse planes)
lateral translation ($\Delta x'$ transverse plane)
axial rotation ($\Delta\theta$ ' transverse plane)
sagittal rotation ($\Delta\theta$ sagittal plane)

Surface markers: posterior-to-anterior translation
(Δy sagittal plane only)

Of particular interest to us was the resolution of relative movements between target and adjacent vertebrae. Since T11 was consistently chosen as the target vertebra, relative movements were calculated with respect to T11. Thus, the relative movements between T10 and T11, and T11 and T12, were estimated as shown in Figure 4, and explained below.

Figure 4 represents a typical absolute movement-time history for a vertebra, as calculated using the technique previously described. The *mean absolute position during preload* was determined for each vertebra by taking the average of 10 sequential preload positions in the middle of the preload phase (over the same time period as that used to estimate the mean preload force). Next, the *maximum absolute position* was deter-

Position (mm or deg)

mean absolute position
during preload

absolute position
at preload'

maximum
absolute position

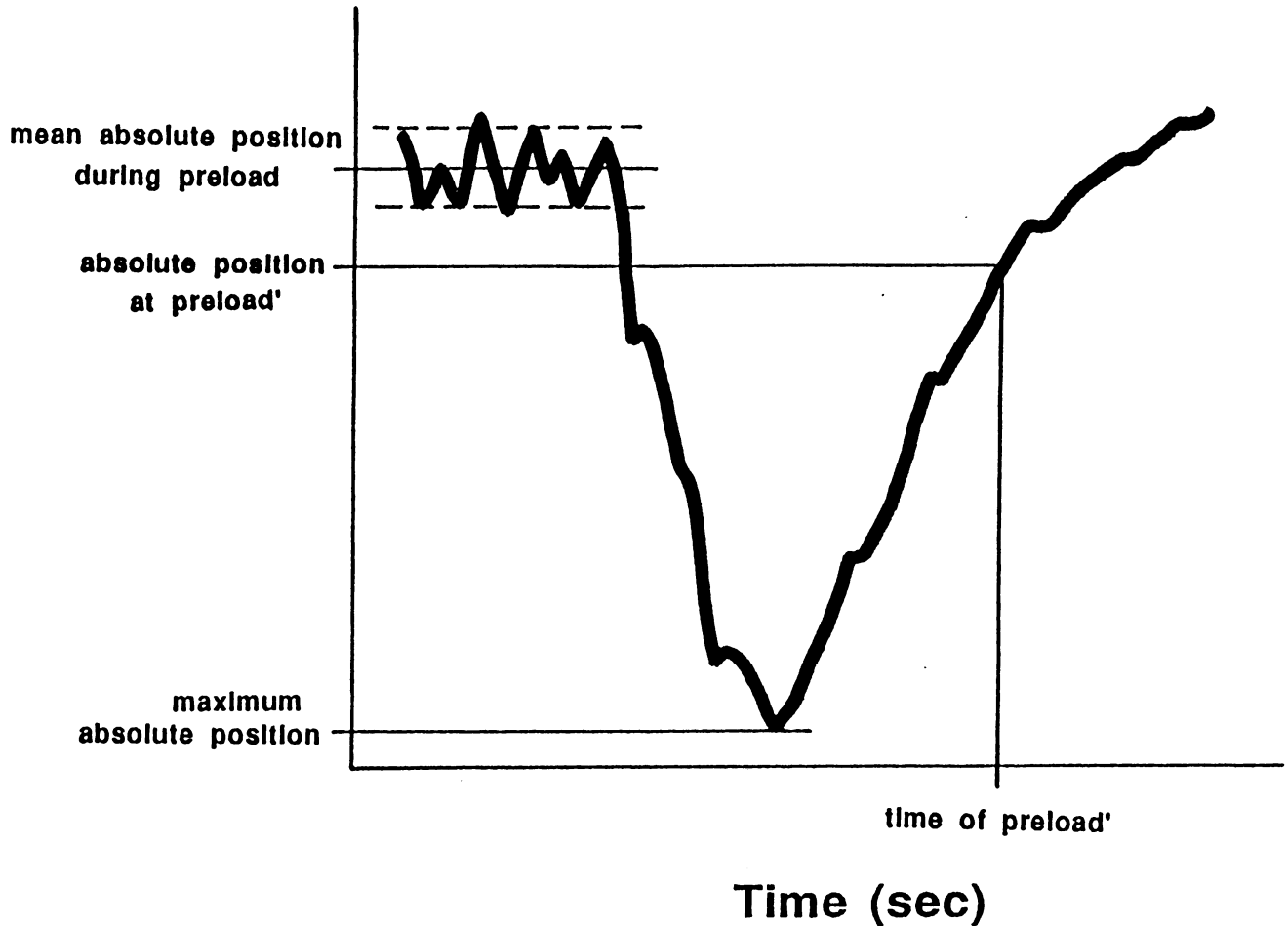time of preload'

Time (sec)

Figure 4 A typical position-time curve for the prescribed SMT is shown. The specific position (either linear or angular) and time characteristics illustrated were obtained for each vertebral body during each SMT, from the embedded bone pins and the surface markers. See text for further explanation.

mined. Finally, the *time of preload'* (the time at which the vertical force dropped to preload') was located on the time axis, and the *absolute position at preload'* of each vertebra, was recorded. The absolute linear and angular movements of each vertebral body were calculated for the preload-to-peak, and peak-to-preload' phases of each SMT as shown below (using T10 as an example),

$$T10_{(max.\ absol.\ position)} - T10_{(absol.\ position\ at\ preload)} = T10_{(absol.\ movement,\ preload-to-peak\ phase)}$$

$$T10_{(absol.\ position\ at\ preload')} - T10_{(max.\ absol.\ position)} = T10_{(absol.\ movement,\ peak-to-preload'\ phase)}$$

In other words, each movement was calculated by the difference

between the final and initial linear or angular positions.

The absolute movements of the adjacent vertebrae were compared to those of the target vertebrae (T10 and T12, and T11, respectively), to give the relative movements during the thrust phase of each SMT as follows,

$$T11_{(abs.\ move.,\ preload-to\ peak)} - T10_{(abs.\ move.,\ preload-to-peak)} = T10T11_{(relative\ move.,\ preload-to-peak)}$$

$$T11_{(abs.\ move.,\ preload-to-peak)} - T12_{(abs.\ move.,\ preload-to-peak)} = T11T12_{(relative\ move.,\ preload-to-peak)}$$

Mean relative movements during the thrust phase of each SMT were calculated for each translation and rotation, by considering the total number of thrusts to a cadaver. Each cadaver was

treated separately. Sample standard deviations were calculated for all sample means. If the mean relative movements during the preload-to-peak phases were significantly different from zero (determined using Student t tests), then relative movements did occur during the thrust of the prescribed SMT (refer to general concept 1. in Introduction section).

The relative movements of the target and adjacent vertebrae were also calculated during the peak-to-preload' phases of each manipulation (using a method analogous to that illustrated above for the preload-to-peak phases of the manipulations), in order to assess the implications of the second general concept introduced in this review. If the vertebrae return to the same relative positions when the peak force drops to the preload' level, then the relative translations and rotations between vertebrae during the preload-to-peak, and peak-to-preload phases should be of equal magnitude and opposite direction (algebraic sign). Therefore, the sum of the successive relative movements of those particular vertebrae should be equal to zero. Significant deviations from zero (determined from paired Student t tests) would be indicative of a failure to return to the same relative position (refer to general concept 2. in Introduction section) following the thrust.

Only p-to-a translations were calculated from the movements of the surface markers. The mean absolute and relative p-to-a translations of adjacent vertebrae were calculated using the surface marker movements and compared (using Student t tests) to those movements derived from the embedded bone pins. Significant differences between the translations calculated by the two methods would be indicative of the extent to which the non-invasive markers were capable of estimating the real movements of the vertebrae, as determined from our criterion markers, the embedded bone pins.

Absolute and relative posterior-anterior translations from accelerometers

Uni-axial accelerometers were used to determine the absolute and relative posterior-to-anterior translations of T10, T11 and T12, non-invasively. These transducers are sensitive to accelerations in one direction only. In these experiments, they were oriented so that they would record accelerations in the posterior-to-anterior direction. The p-to-a accelerations were recorded as voltage (analogue) signals on magnetic tape. Subsequently, these signals were digitized at 2000 Hz and the corresponding accelerations were calculated. P-to-a translations were then calculated by integrating the acceleration-time curves, twice in succession, over the time period of each thrust. The time period of the thrust was determined from the corresponding vertical force-time curve of each thrust. Because only two uni-axial accelerometers were available, accelerometer-derived translations could only be estimated for either T10 and T11, or T11 and T12, for any particular thrust. Relative posterior-to-anterior translations between T10 and T11, and T11 and T12 were estimated using the same technique as that described for the bone pins and surface markers. Thus, with respect to the final

general concept to be discussed in this paper, the mean absolute and relative p-to-a translations of vertebrae, as determined from the accelerometers, were compared (using Student t tests) to those translations derived from the embedded bone pins.

Noise and repeatability

The confidence with which claims can be made about measuring very small relative translations and rotations depends upon the level of random variability in the system in general, and the errors associated with the methodology used. During the preload phases, the linear and angular positions measured for each vertebra fluctuated slightly, despite the fact that the vertical forces applied remained virtually constant. These small fluctuations were quantified, and used as a measure of the random *noise*. The mean preload linear and angular positions, and standard deviations thereof, were calculated for each vertebrae (as previously discussed). The mean of the standard deviations of these preload linear and angular starting positions was determined for each type of movement measured, and used as the indices of noise for the corresponding movement. Thus, if we calculated the noise associated with measuring the posterior-to-anterior translation of a vertebra to be ± 0.30 mm, and we then calculated a mean relative p-to-a translation of + 0.20 mm ± 0.15 mm, for 10 trials to one of the cadavers, the mean relative movement would not be distinguishable from our noise estimate. If however, we calculated a mean relative p-to-a translation of + 0.40 mm ± 0.25 mm, then a Student t test would be used to assess whether or not the mean relative movement was significantly different from zero.

The *repeatability* refers to the accuracy of the digitizing process. It was determined by digitizing all of the thrusts from one of the cadavers, twice. By plotting corresponding x and y coordinates against one another in a cluster diagram, a measure of the repeatability of the digitizing process could be made by comparing the resulting slopes and correlation coefficients. Large deviations from unity in the slopes and the correlation coefficients would indicate poor repeatability, and hence considerable errors due to the digitizing process.

Results

Following the manipulations, sagittal and posterior x-rays were taken to try to verify the location of the bone pins. Only one of the cadavers was available for dissection following the manipulative experiments. Information from both the x-rays and the dissections were used to construct the schematic diagram in Figure 5, which shows the approximate location of the bone pins. The pins were embedded in the bony vertebral arches of T10, T11, and T12. The bone density, as determined qualitatively from the contrast of the bone and soft tissue images on the x-rays, showed that each individual was slightly osteoporotic throughout the thoracic and lumbar region. Figure 6 shows one example of raw force-time and movement-time data from one SMT to each cadaver. These examples reflect the similarity between the mechanical responses of the two cadavers. Mean
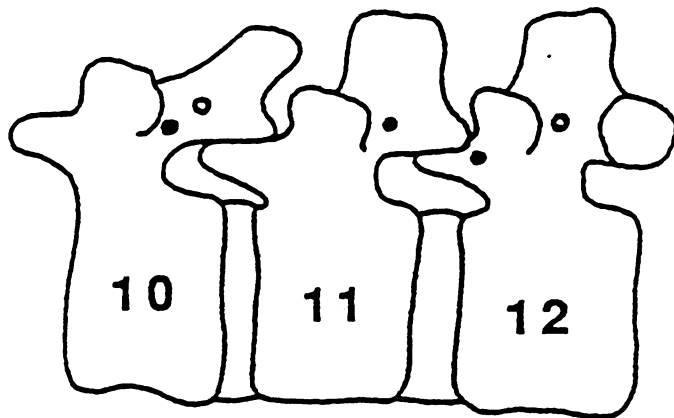
Figure 5 A schematic diagram illustrating the approximate locations of the sagittal and transverse bone pins (open and closed circles respectively) in T10, T11, and T12 of cadaver A (sagittal plane view). See text for further explanation.

preload and peak forces, exerted onto T11 of cadaver A, and B, were 68.9 N ± 17.4 N and 518.5 N ± 70.0 N, and 100 N ± 32.5 N and 534.2 ± 117.6 N, respectively. The force-time and movement-time histories are similar for each vertebral body within each manipulation, except for sagittal rotation. For sagittal rotation, T10 and T11 rotate in the same direction during the thrust, while T12 clearly rotates in the opposite direction.

In Table 1, the means and sample standard deviations of the relative movements between T10 and T11, and, T11 and T12, during the preload-to-peak phases are summarized for both cadavers. Mean relative translations and rotations that were significantly different from zero (where the level of significance was set at 0.05) are indicated by the asterisks. The mean relative sagittal rotations between T10 and T11, and T11 and T12 were statistically significant during the preload to-peak phases for both cadavers. Statistically significant relative axial rotations were also observed, particularly between T11 and T12. Less substantial, albeit statistically significant relative lateral and posterior-to-anterior translations were also observed, however, these means were often below the corresponding noise values for the same movements. The noise estimates were ± 0.35 and ± 0.38 mm for posterior-to-anterior and lateral translations respectively, and ± 0.14 and ± 0.16 degrees for sagittal rotations respectively. The digitizing process was repeatable, since the mean slopes and mean correlation coefficients associated with plotting the x and y coordinates of successively digitized SMTs were not significantly different from unity (0.909 ± 0.119 and 0.913 ± 0.083 respectively, where $n = 54$, for 9 x, y pairs in 6 SMTs).

To determine whether the relative positions of the vertebral bodies were the same previous to, and following the manipulative thrusts, the relative movements between T10 and T11, and, T11 and T12 during the preload-to-peak and subsequent peak-to-preload' phases were compared using paired Student t tests and a significance level of 0.05. The results of these comparisons, combined for both cadavers, are summarized in Table 2.

TABLE 1
Mean relative translations and rotations (and sample standard deviations) between T10 and T11, and T11 and T12, during the preload-to-peak phases of SMTs to T11

Relative Movement	Cadaver A ($n = 8$)		Cadaver B ($n = 6$)	
	T10T11	T11T12	T10T11	T11T12
P-to-a translation, mm	−0.3 ± 1.3	−0.6 ± 0.7*	+0.3 ± 0.4*	−0.3 ± 0.2*
Lateral translation, mm	+0.4 ± 0.9	−0.4 ± 0.5*	+0.6 ± 0.4*	+0.1 ± 0.3
Axial rotation, deg	0.0 ± 0.3	+0.4 ± 0.4*	−0.2 ± 0.1*	+0.3 ± 0.2*
Sagittal rotation, deg	+0.5 ± 0.3*	−1.5 ± 0.1*	+0.3 ± 0.2*	−1.9 ± 0.2*

Noise associated with measuring p-to-a translation, lateral translation, axial rotation, and sagittal rotation was ± 0.35 mm, ± 0.38 mm, ± 0.14 deg, and ± 0.16 deg, respectively.

* Statistically significant (at a significance level of $p = 0.05$).

The null hypothesis, that the relative movements between vertebral bodies during the thrust and release phases were of equal magnitude and opposite direction (algebraic sign), was accepted for every type of relative movement except sagittal rotation between T11 and T12 (as indicated by the asterisk). The mean sagittal angle between T11 and T12 following the manipulations, was not the same as that immediately previous to the manipulative treatments.

Figure 7 illustrates an example of the absolute posterior-to-anterior translation for T12, as derived from the bone pins, surface markers and accelerometers. Typically, estimates from the surface markers were slightly less than those from the bone pins for any trial. Accelerometers further underestimated the absolute posterior-to-anterior translations of any vertebral body they were associated with.

Table 3 shows a summary of the comparisons between the absolute and relative posterior-to-anterior translations of vertebral bodies as determined by the invasive (bone pins) and non-invasive (surface markers and accelerometers) methods, for both cadavers. Absolute p-to-a translations of vertebrae were estimated using each method. The mean differences between the bone pins and surface markers, and the bone pins and accelerometers (Δ absolute bp-sm, and Δ absolute bp-acc, respectively) were calculated, and were statistically assessed for significance differences from zero (using paired Student t tests and a significance level of 0.05). Both the surface markers and accelerometers significantly underestimated the absolute posterior-to-anterior translations (as indicated by the asterisks) of the vertebrae as compared to the bone pins, during the manipulations. The mean relative p-to-a translations between adjacent vertebral bodies during manipulations to both cadavers, as determined from the bone pins, surface markers, and accelero-

TABLE 2
Means of the differences between the relative translations and rotations between T10 and T11, and, T11 and T12, during the preload-to-peak, and peak-to-preload' phases of SMTs to T11 (cadavers A and B combined, $n = 14$)

Relative Movement	T10T11	T11T12
P-to-a translation, mm	$+0.4 \pm 1.0$	$+0.0 \pm 0.8$
Lateral translation, mm	$+0.1 \pm 0.7$	$+0.0 \pm 0.7$
Axial rotation, deg	$+0.1 \pm 0.4$	$+0.1 \pm 0.5$
Sagittal rotation, deg	$+0.1 \pm 0.4$	$-0.3 \pm 0.2*$

* Statistically significant (at a significance level of $p = 0.05$).

TABLE 3
Mean differences between the absolute and relative p-to-a translations of T10, T11 and T12 (in mm), from the bone pins (bp), surface markers (sm), and accelerometers (acc).

Δ absolute bp-sm	Δ absolute bp-acc	relative bp	relative sm	relative acc
$-1.1 \pm 1.5*$	$-3.1 \pm 1.7*$	0.0 ± 0.9	-0.2 ± 0.9	-0.9 ± 3.0

For Δ absolute bp-sm, and Δ absolute bp-acc, $n = 20$.
For relative bp, relative sm, and relative acc, $n = 10$.

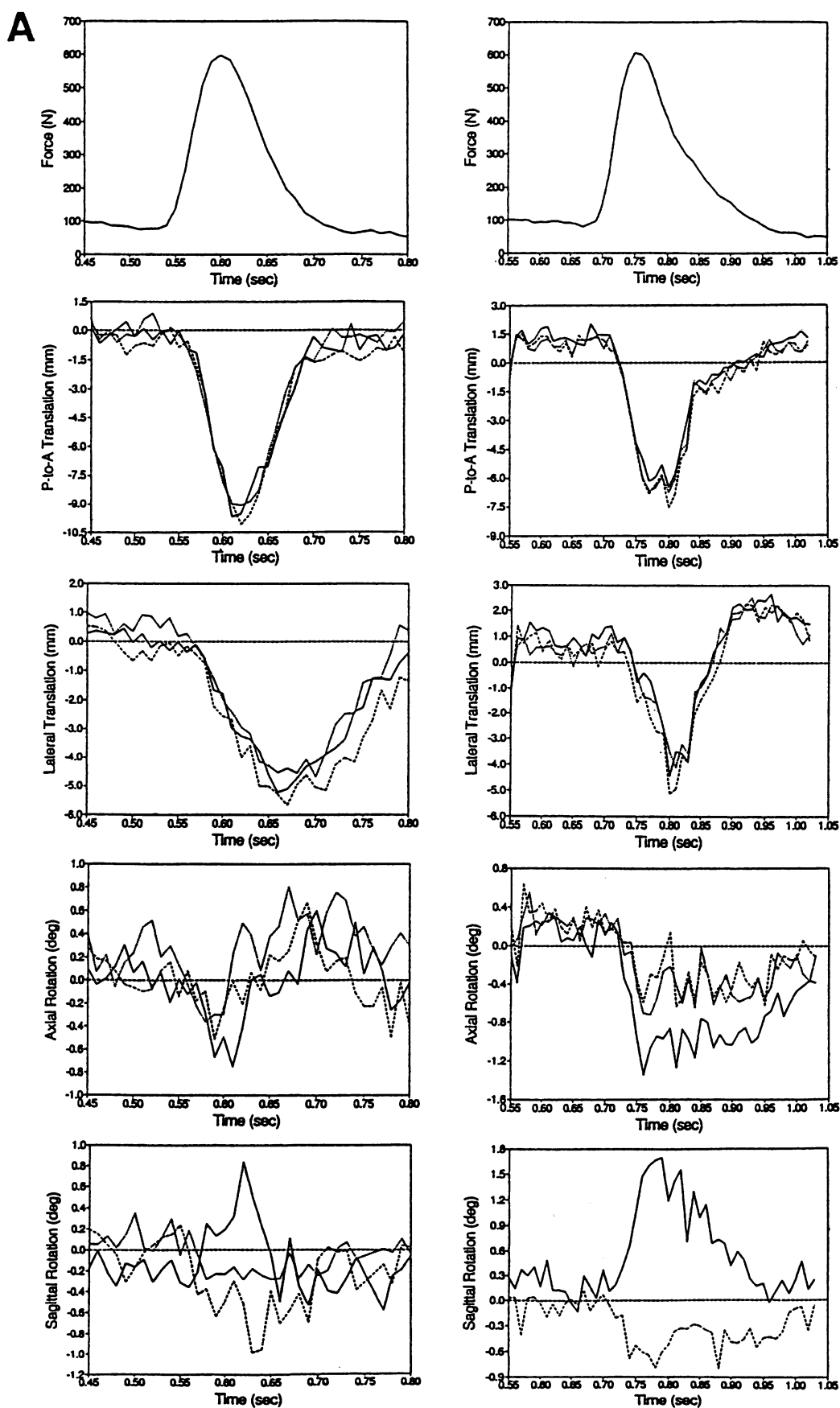* Statistically significant (at a significance level of $p = 0.05$).

Figure 6 The vertical forces and absolute movements of T10, T11 and T12 (dashed line, dotted line, and solid line, respectively) are shown for one SMT to each cadaver (A and B respectively). See text for further explanation.

meters, are also shown in Table 3 (relative bp, relative sm, and relative acc, respectively). Each method yielded mean relative p-to-a translations that were not significantly different from zero (for a level of significance of 0.05). The sample standard deviation associated with the mean relative p-to-a translation derived from the accelerometers was quite high.

Discussion

Although we acknowledge the wide variety of manipulative treatment modalities available to the clinician, as biomechanicians, we can and do, reduce them all to their fundamental mechanical elements. Thus, the clinician delivers a force of varying magnitude, direction and duration, to a predetermined location on the vertebral column. The vertebral column, which may be viewed as a composite structure involving rigid and viscoelastic elements (the vertebrae, and the intervertebral discs and ligaments, respectively), can respond in a number of ways. It can fracture, which is clearly not the goal of the clinician, or, it can deform. The deformation behaviour of a complex structure such as the vertebral column continues to present a challenge to researchers.

The goal of this work was to investigate the manner in which the vertebral column would deform under the influence of a clinically-relevant spinal manipulative thrust. Since the vertebral bodies are much stiffer than the structural elements connecting them, it was our impression that the latter would deform more readily. Thus, our method of detecting spinal deformation was to measure the absolute, and more importantly, the relative movement of the vertebral bodies during SMT. By using unembalmed cadavers, we could accurately measure the movement of the vertebrae of interest. It was not our intention to use the information derived from these experiments to make direct predictions about the mechanical responses of the vertebral column to SMT in live patients. Rather, we were concerned about the potential for detecting the small rapid movements that we suspected to coincide with the rapidly-applied SMTs that are often used during clinical adjustments.

Under the influence of the prescribed SMT, considerable absolute movements were observed for the vertebral bodies of the unembalmed cadavers used in this investigation. During the preload-to-peak phases, absolute translations of 8–12 mm, and 4–6 mm, in the posterior-anterior, and right lateral directions
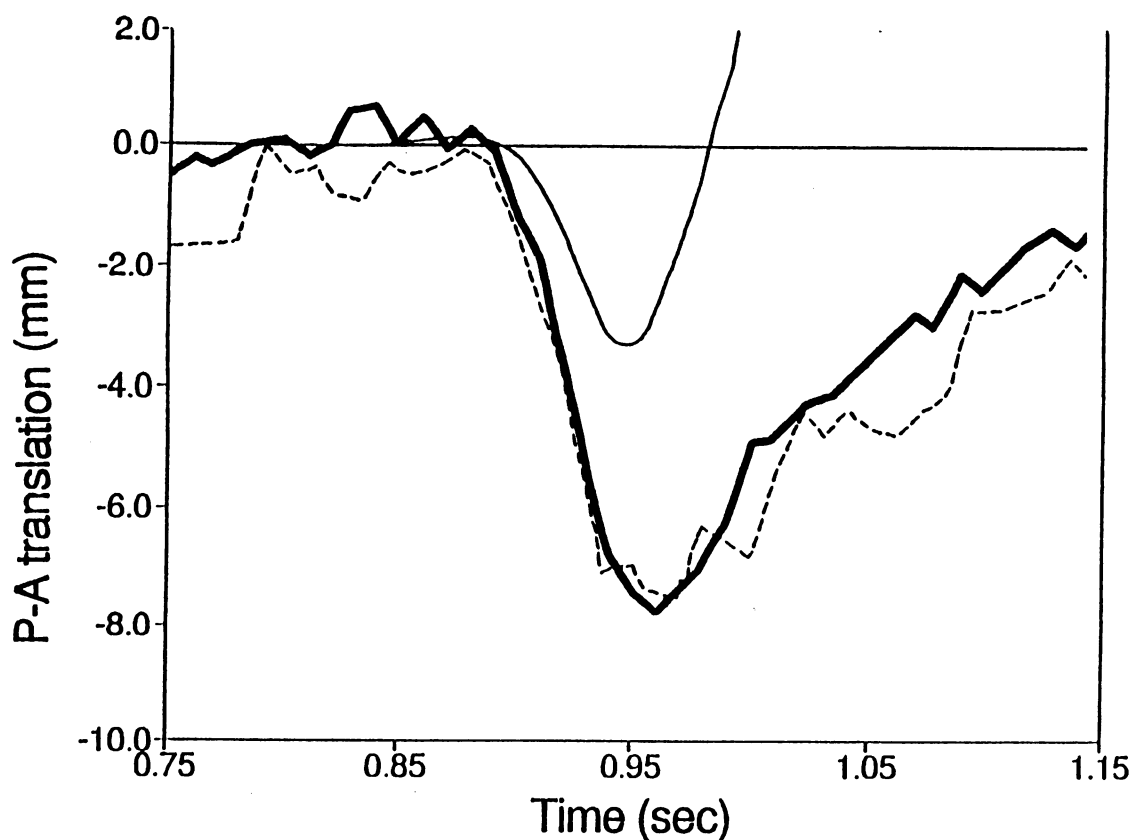

Figure 7   The absolute posterior-to-anterior translations of T12, as determined from the bone pins, surface markers and accelerometers, (thick solid line, thin dotted line, and thin solid line, respectively) are shown for one SMT. See text for further explanation.

respectively, were observed for all vertebrae (see Figures 6A and B).

The mean relative movements between T10 and T11, and, T11 and T12, and sample standard deviations thereof, during the preload-to-peak force phases in both cadavers, are summarized in Table 1. The mean posterior ($-y$ and $-y'$, Figures 3A and B, respectively) translation of T11, the target vertebrae, was in general slightly greater than the two adjacent vertebral bodies during the thrust phase. The SMT induced significantly greater right lateral translations in T11, than in T10 and T12. All vertebrae were rotated in a right ($- \theta'$, clockwise, Figure 3B) axial direction during the thrust phases of the SMTs. However, the right axial rotations of T12 were significantly greater than those of T10 and T11. Most dramatically, the SMTs induced significant relative sagittal rotations between T10 and T11, and, T11 and T12 in both cadavers. T10 and T11 (to a greater degree), rotated in a inferior ($-\theta$, clockwise, Figure 3A) direction, while T12 clearly rotated in a superior ($+\theta$, counterclockwise, Figure 3A) direction.

It would appear that during the thrust phases of the prescribed SMTs, localized hyperextensions of the intervertebral joints T10T11 and T11T12, were responsible for the most pronounced relative movements. In general, the deformation behavior of T11T12 differed from that of T10T11. The latter two vertebral bodies tended to react as a unit to the applied forces of the clinician. The response of T12 was clearly different than the responses of the other two vertebral bodies, particularly with respect to sagittal rotation. These observations are probably due to the unique nature of the articular facet joints of T12, the transitional vertebra. Figure 8B shows a schematic representation of the orientations of the facet joints of the target and adjacent vertebral bodies. Both T10 and T11 have transversely-oriented facet joints. T12 however, has transversely- and sagittally-oriented superior and inferior facet joints respectively. Typically, the transversely-oriented facet joints tend to allow some relative axial rotation, but deter relative sagittal rotation. In contrast, the sagittally-oriented facet joints allow for relative sagittal rotation, but hinder relative axial rotation. In the lumbar region, while relative sagittal rotations can be substantial, relative axial rotations are almost totally excluded.[5] Thus, the potential for the sagittal rotation of T12 is greater than that of T10 and T11. The significantly greater axial rotation of T12, compared to that of T11 cannot be explained.

It would be useful to compare the measured relative movements between vertebrae that occur during SMT, to the normal ranges of motion observed on the corresponding spinal level. However, this is difficult to do because the chiropractor already endeavours to move the target vertebrae through to the limit of physiological range of motion during the preload phase of the SMT. Thus any relative movements measured in this study, occur outside the normal physiological range of relative motion, and thus are beyond the values cited in the literature for the
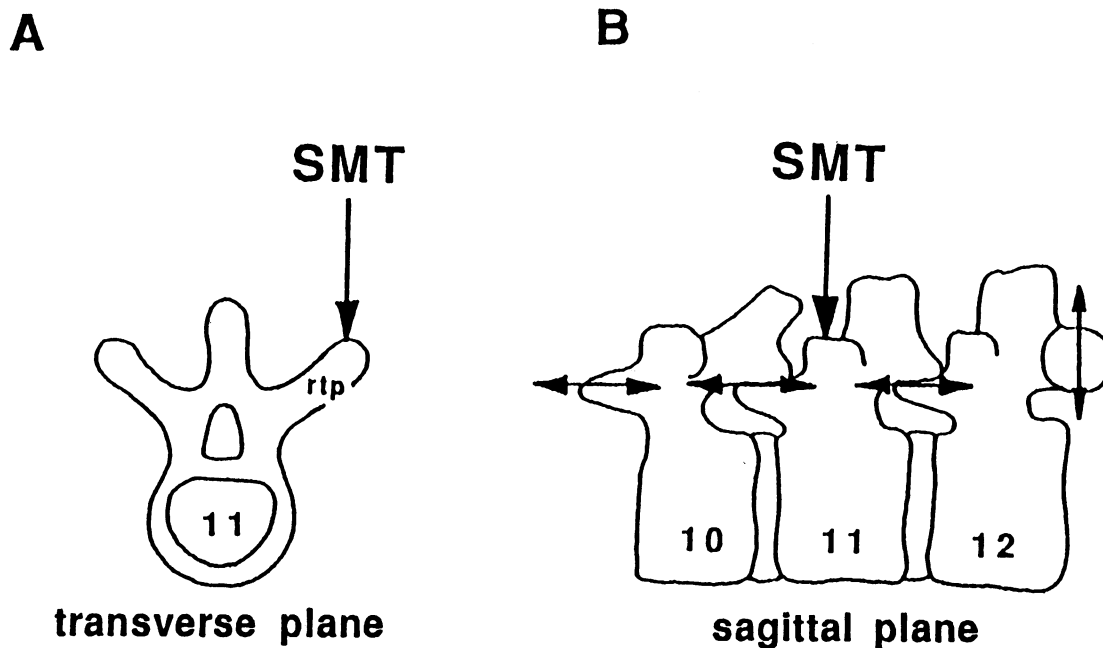
A   **B**

Figure 8   The orientation of the prescribed SMT with respect to T10, T11, and T12 is shown in inferior and sagittal views (transverse plane A and sagittal B, respectively). The right transverse process of T11 is indicated by rtp. The orientations of the superior and inferior articular facet joints of T10, T11 and T12, are shown by the connecting arrowheads in B. See text for further explanation.

normal range of motion of a motion segment. Moreover, the physiological range of relative sagittal rotation is expressed as the **combined** angular range of flexion and extension. Clearly, intervertebral flexion is not occurring during the manipulations. However, it is not possible to say how much of the flexion/extension range of motion can be apportioned to the intervertebral extension alone. For the motion segment T11T12, the limit of the flexion/extension range is 6–20 degrees, and the representative angular range is 12 degrees.[5] Thus, a relative extension of the motion segment T11T12 of 1.5–2 degrees, may represent a substantial percentage of the normal range of intervertebral extension T11T12.

Another question of interest is whether or not the SMT induces some permanent or semi-permanent change in the relative position of the target and adjacent vertebral bodies. We attempted to address this question by comparing the relative movements of vertebral bodies between preload-to-peak, and peak-to-preload', phases of the prescribed SMTs. These data are summarized in Table 2. Significant differences between the relative movements of adjacent verebrae during the preload-to-peak, and peak-to-preload' phases of the manipulations were observed only for the relative sagittal rotations between T11 and T12. The mean sagittal angle between T11 and T12 following manipulations, was not the same as that immediately previous to the manipulative treatments. Interestingly, the relative sagittal rotations between these vertebral bodies were clearly the most striking relative movements during the thrust phases of the prescribed SMTs. At present, we are unable to comment further upon the possible significance of this finding, in terms of a potential mechanical mechanism responsible for the efficacy of SMT. In the short-term at least, the changes in the relative sagittal position of T11 and T12 do not appear to be completely reversed at the end of SMT.

Figure 7 illustrates an example of the posterior-anterior translations of T12 as measured by the embedded bone pins, surface markers and uni-axial accelerometers. A summary of these data from all trials is shown in Table 3. Both non-invasive techniques significantly underestimated the absolute p-to-a translations of the vertebral bodies that were calculated from the movements of the embedded bone pins. There were no significant differences between the relative p-to-a translations between T10 and T11, and, T11 and T12 using any of the techniques. In general however, the surface markers yielded absolute and relative movements that more closely mimmicked the movements of the bone pins, than the corresponding values obtained using the accelerometers. The uni-axial accelerometers are sensitive to accelerations in one direction only. Movements that would tilt the accelerometers away from their direction of sensitivity would reduce their capacity for transducing acceleration. The axial and sagittal rotations of the vertebrae (and in fact of the entire cadaver) that occurred during the prescribed SMTs would have such an effect, by tilting the accelerometers away from the vertical orientation, and thus would contribute to the observed underestimation of the absolute posterior-to-anterior transla-

tions of the target and adjacent vertebral bodies. Additionally, the process of integrating the acceleration signals twice in succession in order to calculate p-to-a translations would result in a further enhancement of any errors associated with the raw acceleration signal. The mean relative p-to-a translation between adjacent vertebrae, as determined using the accelerometers, had a large associated sample standard deviation (see Table 3).

T11 was always the target vertebral body for these manipulations. In general, the bone pin movements showed that the posterior-to-anterior translations of T11 (negative algebraic sign) were greater than those of T10 and T12, during the thrust phases of the SMTs. However, the accelerometer-derived p-to-a translations showed that sometimes T11 translated to a lesser extent than the adjacent vertebra. As stated in the Methodology section of this review, only two accelerometers were available. One of the accelerometers was taped onto the skin over the spinous process of the target vertebra T11. The other accelerometer was first taped over T12, and after five manipulations, was moved to be taped over T10, where another five manipulations were performed on T11. The repositioning of the second accelerometer appeared to have been responsible for the change in direction of the relative p-to-a translations of the adjacent vertebrae. Because all trials using both cadavers were combined in the calculations shown in Table 3, this effect appears to have manifested itself as the large sample standard deviation of the relative p-to-a translations of vertebral bodies, as determined from the accelerometers. Again, this illustrates the necessity for correct initial positioning, and maintenance thereof, of accelerometers with respect to their direction of sensitivity, if indeed uni-axial accelerometers are to be used as non-invasive transducers of vertebral displacements.

Although this study was conducted with unembalmed cadaveric specimens, we feel that similar trends in relative movements would be observed for the same type of SMT to a live patient, because, as stated previously, the ways in which two vertebral bodies can move relative to one another depends ultimately upon the bony geometry of the articular facet joints, which do not change between the living and cadaveric states. In the cadaver, only the passive musculo-skeletal components (such as passive muscle and tendon forces, ligament forces and bone contact forces) can resist the forces exerted by the clinician. During manipulative treatments to a patient, the active resistive components (such as active muscle and tendon forces, and thoracic and abdominal pressures) may exert bracing or stabilizing forces, over and above those afforded by the passive components. The specific force-deformation responses, whether they be linear or angular, may be expected to differ between the living and cadaveric states. Interestingly however, the vertical forces exerted during genuinely clinical treatments, as measured by Herzog et al. (1993), do not differ substantially from those force components recorded during these manipulations to cadavers. Herzog et al. (1993) measured mean preload and peak forces during manipulative thrusts to T4 of 139 N ± 46 N and

399 N ± 119 N respectively. Here, we reported mean preload and peak forces exerted during the same type of manipulative thrusts to T11 in cadaver A, and B, of 68.9 N ± 17.4 N and 518.5 N ± 70 N, and, 100.0 N ± 32.5 N and 534.2 N ± 117.6 N, respectively. Thus, we must consider the possibility that significant relative translations, and particularly rotations (especially in the sagittal plane), may occur in live patients that are subjected to the same type of manipulative thrust used in this study. Measuring these relative movements in live patients would require a considerably more complex non-invasive method than our point-marker method. We do feel, however, that a viable system that could be used in a dynamically-relevant clinical situation may be designed, using a combination of several types of displacement, velocity and acceleration transducers, all mounted on a single rigid structure.

Conclusions and future work

In this review, we have discussed our work with respect to the measurement of relative movements between vertebral bodies during clinical-type SMTs to unembalmed cadavers. By using cadaveric specimens, accurate measurements of the vertebral movements were possible using bone pins. We found that for the prescribed SMT, relative sagittal rotations between vertebrae were particularly striking. These results could be explained, at least partially, by considering the morphology of the target and adjacent vertebral bodies, particularly with respect to the articular facet joints. We speculate that a similar trend in relative movement may occur in the living patient. We believe that this is the first time that relative rotations have been shown to be significant for any type of SMT deliverd to the human vertebral column. This was not an obvious result, considering that the major thrust of the prescribed SMT was in the posterior-to-anterior direction. However, from the results obtained in this study, it appears that relative rotations of vertebrae may be of importance in any discussion of potential mechanisms for the efficacy of SMT.

Further to our general interests in the mechanics of the spine during SMT, we are currently investigating how the forces applied during SMT are propagated through the vertebral column. By applying similar SMTs to T10 and T12, we can investigate the relative movements of vertebral bodies (T12 or T10 respectively) which are not immediately adjacent to the target vertebra.

Within the same mechanical framework, we are also in the process of investigating the effects of changing the rate of the

applied forces on the relative movements that may occur between vertebral bodies. Most biological structures display viscoelastic behavior.[7] That is, the faster they deformed, the stiffer they become. The chiropractor is faced with an interesting problem. The applied SMT must be delivered sufficiently fast in order that the treatment be delivered before the reflex contraction of the back muscles of the patient occurs. The reflex contraction of the back muscles would tend to stiffen the spinal column. However, there is the potential that increasing the speed of delivery of the SMT is associated with an increase in the stiffness of the intervertebral joints. If the desire of the clinician is to effectively treat the patient with the minimum amount of force, then there is potentially an optimal rate at which the SMT must be applied. This optimal rate would circumvent back muscle reflexes, yet would be slow enough to prevent significant viscoelastic stiffening of the joints. We will address these topics in the future.

Acknowledgements

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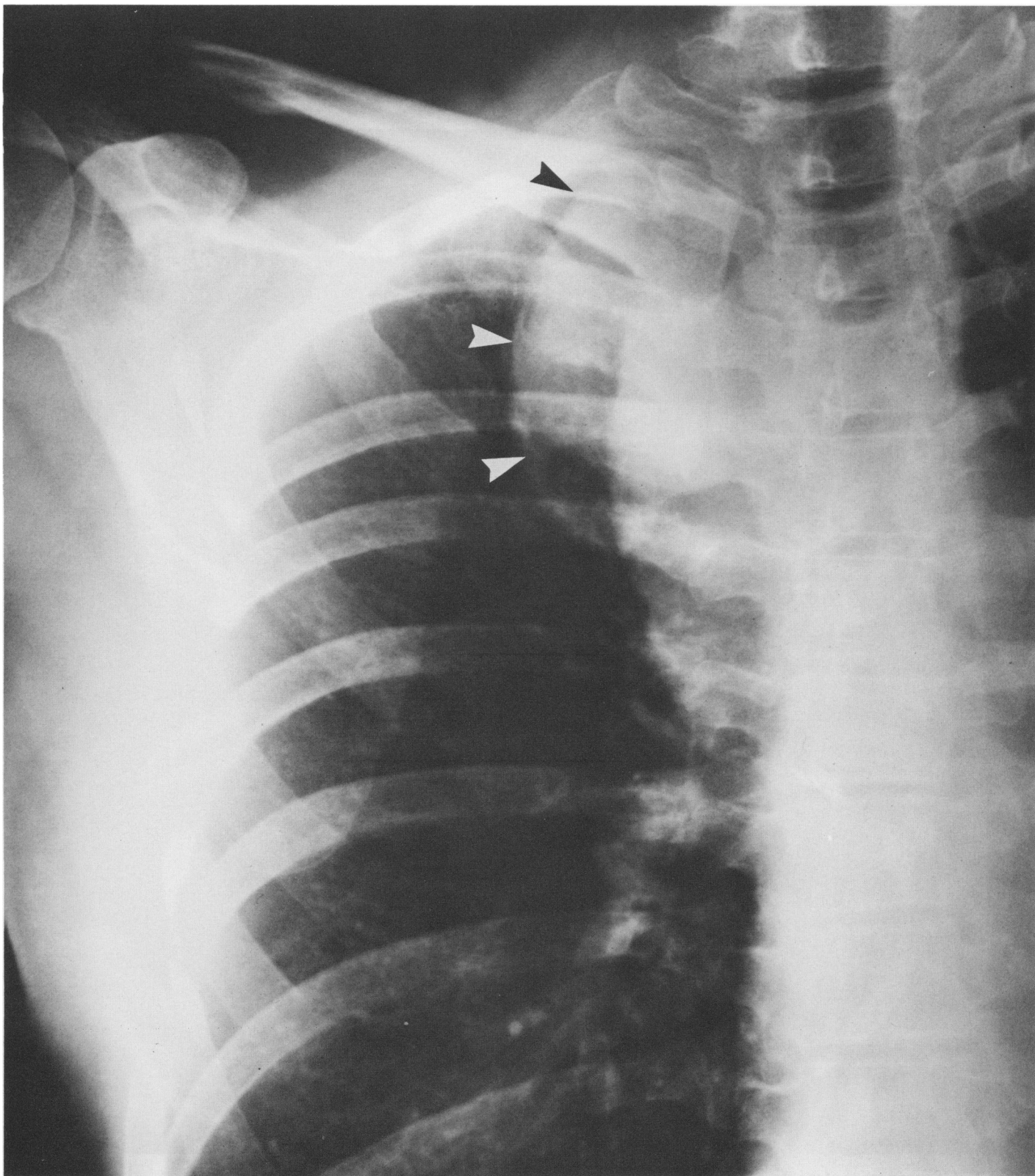
Figure 2   Anteroposterior rib radiograph shows a mass in the upper lung field. (arrows)